

# Can bubbles sink ships?

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I investigate the interplay between the buoyancy force and the upwelling (or drag) force which act on a floating object when bubbles are rising through a body of water. Bubbles reduce the buoyant force by reducing the density of the water, but if they entrain an upwelling flow of water as they rise, they can produce a large upward drag force on the floating object. In an upwelling flow, our model ship (density =  $0.94 \text{ g/cm}^3$ ) floats in a foam whose density is only  $0.75 \text{ g/cm}^3$ . Comparing results with and without upwelling currents is an interesting demonstration and has real-world applications to ships in the ocean. © 2010 American Association of Physics Teachers.  
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## I. INTRODUCTION

Reducing the buoyancy of floating objects with bubbles is a fascinating laboratory demonstration and models the results of large-scale methane gas releases in the ocean. Archimedes' principle states that the buoyant force on an object submerged in a fluid equals the weight of the fluid displaced by the object.<sup>1</sup> The presence of gas bubbles in the supporting fluid reduces the density of the fluid, thereby decreasing the weight of the displaced fluid. This decrease lessens the buoyant force on the floating object, potentially causing it to sink. Denardo<sup>2</sup> illustrated this effect in experiments where he carefully eliminated circulating currents, as shown schematically in Fig. 1. In an open environment, as shown in Fig. 2, the water is able to circulate, moving upward with the bubbles, then moving outward and downward in the surrounding water, and then moving in and upward again with the bubbles. We will see that these currents, caused by rising bubbles which entrain water, exert an upward force on a floating body.

Such "storms" of bubbles rising through bodies of water have been observed, for example, in the 1986 Lake Nyos disaster in Cameroon.<sup>3</sup> A similar mechanism could operate in the oceans: enormous quantities of methane could be released in the ocean by either exsolution of methane dissolved in the water column<sup>4</sup> or melting of methane hydrates on the sea floor.<sup>5</sup> Either of these events could create a huge rising storm of methane bubbles, which would be a threat to ships in the area. May and Monaghan<sup>6</sup> considered this threat by studying the effect that a large single bubble can have on a two-dimensional ship floating in a tank with only one horizontal dimension. In my tests, I use a tank with two horizontal dimensions and many smaller bubbles to better simulate the ocean. These tests reveal that the force exerted by the upwelling current can be significant. I also discuss the scaling of the forces acting on the ship from the size of my model to the size of real ships in the ocean.

## II. EXPERIMENTAL APPARATUS

The tank is a 10 gal aquarium connected by a flexible plastic hose to an Aquatic Ecosystems air blower, which can blow  $10\text{--}15 \text{ ft}^3/\text{min}$  of air against a pressure of 8 in. of water. The hose attaches to a plastic grill, which was designed to support the filtering gravel in the aquarium (see Fig. 3). The grill at the bottom of the tank was taped at its edges to confine the bubble flow to a smaller area of about  $450 \text{ cm}^2$  (the total base area is about  $1100 \text{ cm}^2$ ). This sys-

tem simulates a methane release in the ocean by creating an area of froth and bubbles surrounded by calmer water. The model ship consists of the protective plastic canister for a 35 mm film roll filled with pennies to adjust the density, with a Silly-Putty cone on the bottom to emulate the sloped hull of a ship (see Fig. 4). The ship is buoyant and floats with about 6% of its length above the water (its density is  $45.5 \text{ g}/48.5 \text{ cm}^3 = 0.94 \text{ g/cm}^3$ ). The ship is held in a mechanical guide, which limits horizontal movement but allows the ship to move vertically. The guide is a simple K'NEX (Ref. 7) structure that consists of four vertical rods that confine the ship. The ship and the guide are placed on top of the grill inside the aquarium, and the aquarium is filled halfway with water. When the blower is turned on, it pushes air into the bottom of the tank and up through the grill, creating a relatively uniform field of bubbles underneath the floating ship. We estimate the foam to be 20%–30% air by observing the rise in the water level while the pump is on and comparing to the resting water level (pump off).

For the confined geometry experiment, a cylindrical barrier is placed around the ship guide. This barrier, made from a plastic sheet rolled into a cylinder, sits on the bottom grate and stops circulating currents by blocking lateral movement of the water, as shown schematically in Fig. 5. Inside the barrier there is not enough space for large currents to form (these need room for the water to rise in the middle, flow to the outside, sink down to the bottom, and then rise to the top again). Instead, bubbles rise through the water without entraining an upward water flow.

## III. EXPERIMENTAL RESULTS

With the confining barrier removed, the ship floating in the guide, and the air blower on, we found that the ship did not sink. Instead, it jittered up and down, staying close to the surface of the foamy water. Its rapid movements suggest that it is subject to a large but variable upward force, which adds to the buoyant force to counteract gravity and keep the ship afloat. We suspect that this force is a drag force caused by moving water entrained by the bubbles. Figure 6 gives a sense of the strength of the upwelling current and shows the bubble density. The ship guide is partly visible but not the ship itself.

To investigate whether the force is an upwelling drag force, we constructed a "bubble blocker" by taping off a few square centimeters of the grill directly underneath the ship to reduce the upwelling current in the vicinity of the ship. We

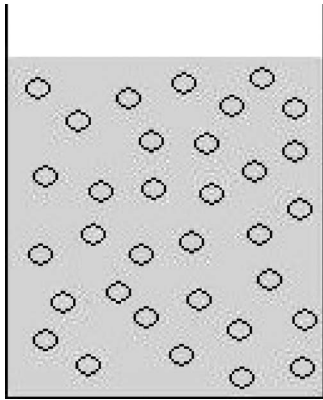


Fig. 1. Confined geometry with bubbles rising through still water.

also experimented with and without the Silly-Putty cone on the ship. We found that the addition of either the cone or the bubble blocker or both contributed to the ship riding a little lower in the water but did not induce sinking. These observations are consistent with the upward force being an upwelling drag force.

We further tested this hypothesis by adding a cylindrical barrier to create a confined geometry around the ship holder. The uniformity of the bubbles inside the cylindrical plastic barrier eliminates the circulating currents. For this setup the ship sank completely, rested on the bottom, and remained on the bottom for several seconds after the pump was turned off, and the bubble density dropped. This action confirmed that the drag force was supporting the ship. Without circulating currents, the ship sank in the low density foam. The ship even stayed on the bottom for most of the blower's wind down time, confirming that our apparatus generates a bubble density many times greater than that necessary to sink the ship (in the absence of the upwelling current). This experiment is a good demonstration for students, because by removing and replacing the barrier, we can alternate between unconfined and confined geometries and observe the ship floating (unconfined) or sinking (confined).

#### IV. THEORY

In the confined geometry (plastic cylinder in place, no circulating currents, and no upwelling water), the model ship sank convincingly. In the unconfined geometry (no plastic cylinder, circulating currents, and large upwelling of water), the model ship did not sink. The factor that appears to keep the ship afloat in the unconfined geometry is the drag force caused by the upwelling surge of water entrained by the ris-

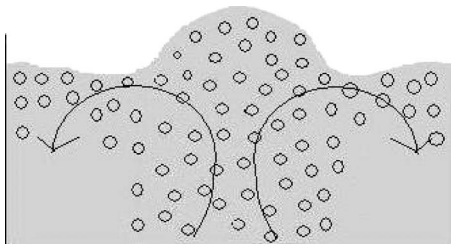


Fig. 2. Unconfined geometry with circulating currents of water.

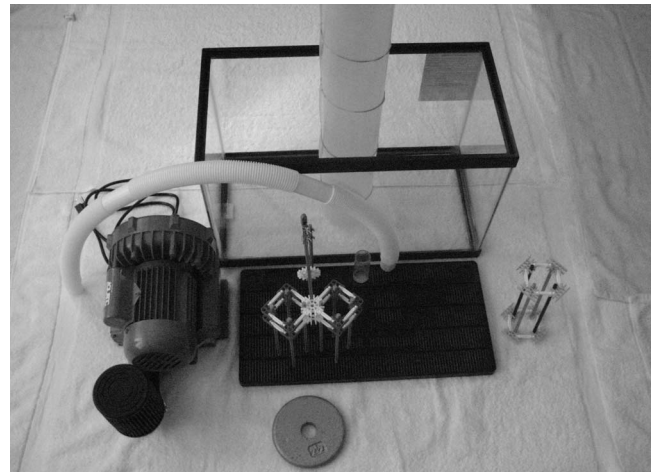


Fig. 3. Apparatus consisting of an air blower, flexible hose, aquarium, confining cylinder, plastic grill, boat guides made from K'NEX (Ref. 7), and weight.

ing bubbles. We estimate the magnitude of this upward drag force to confirm that it could plausibly support the model ship.

The drag force is

$$F_{\text{drag}} = \frac{1}{2} \rho v^2 C_{\text{drag}} A, \quad (1)$$

where  $\rho$  is the mass density of the fluid,  $v$  is the velocity of the object relative to the fluid,  $C_{\text{drag}}$  is the drag coefficient, and  $A$  is the cross-sectional area. The cross-sectional area of the model ship is  $10.7 \text{ cm}^2$ . The drag coefficient for form drag alone is rarely found to be greater than 2, but skin friction along the side area of the model ship adds drag as well, and thus we use a total drag coefficient in the range of 2–3 to include the contribution from the sides. Because we estimate the fluid to be approximately 25% air and 75% water, the density is  $0.75 \text{ g/cm}^3$ . By recording the time it took

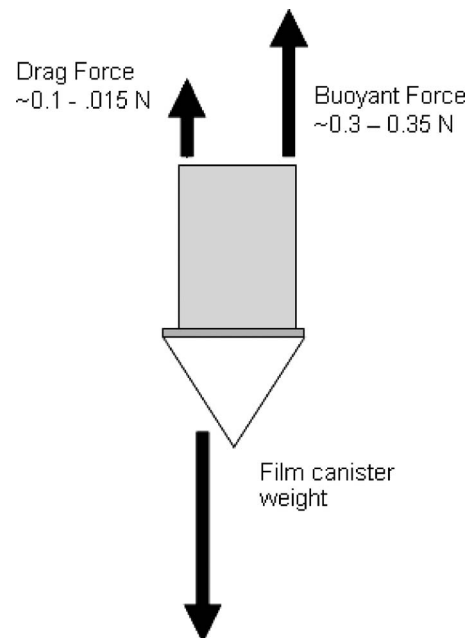


Fig. 4. The model ship and the forces acting on it.

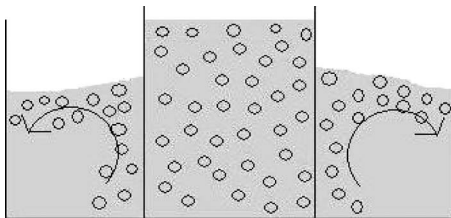


Fig. 5. The confining cylinder creates a confined space inside an unconfined area.

bubbles to rise from the bottom of the tank to the top, we determine an upwelling speed of  $35 \pm 10$  cm/s. Using these estimated values, we find the upward drag force to be

$$F_{\text{drag}} = 1/2(0.75 \text{ g/cm}^3)(35 \text{ cm/s})^2(2.5)(10.7 \text{ cm}^2) \\ = 0.12 \text{ N.} \quad (2)$$

The greatest source of uncertainty in this value is the upwelling velocity because this velocity varies as the water surges upward in an irregular way. In addition, the drag force depends on the square of this velocity. The  $\pm 10$  cm/s variation in the upwelling velocity corresponds to a variation of  $+0.08$  N/ $-0.06$  N in the force.

The model ship has a mass of 45.5 g and a volume of  $48.5 \text{ cm}^3$ . Therefore its weight is 0.446 N, and the buoyant force (for a fluid density of  $0.75 \text{ g/cm}^3$ ) is 0.356 N. Thus, a force of 0.09 N is enough to keep it afloat, and the upwelling force is confirmed as a plausible candidate.

It is interesting to see if these forces remain similar in magnitude when we scale by a factor of about 1000 from the model ship (a few centimeters in length) to a real ship (a few tens of meters in length). The bubbles scale from a few millimeters in diameter to a few meters in diameter, which seems a plausible size for methane bubbles in a dramatic oceanic release. For this scaling, both the mass and the buoyant force of the ship increase by a factor of  $10^9$ . The drag force will also scale by  $10^9$  because the speed at which bubbles rise scales with the square root of their diameter,<sup>8</sup> and the area of the ship scales with the square of the length. Therefore, it appears that for a large ship, the drag force will remain comparable to the buoyant force and to the force of gravity, just as it is for the model ship. Whether the ship sinks or not depends on the complex interplay between these



Fig. 6. The “bubble storm” including a violent upwelling current.

three forces, as well as such practical matters as whether the ship fills with water or breaks up in the violence of a bubble storm.

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<sup>1</sup>R. Serway, *Physics for Scientists and Engineers* (Saunders College Publishing, Philadelphia, 1996).

<sup>2</sup>B. Denardo, L. Pringle, C. DeGrace, and M. McGuire, “When do bubbles cause a floating body to sink?,” *Am. J. Phys.* **69**, 1064–1072 (2001).

<sup>3</sup>G. W. Kling *et al.*, “The 1986 Lake Nyos gas disaster in Cameroon, West Africa,” *Science* **236**, 169–175 (1987).

<sup>4</sup>G. Ryskin, “Methane-driven oceanic eruptions and mass extinctions,” *Geology* **31**, 741–744 (2003).

<sup>5</sup>K. C. Hester and P. G. Brewer, “Clathrate hydrates in nature,” *Annu. Rev. Marine Sci.* **1**, 303–327 (2009).

<sup>6</sup>D. May and J. Monaghan, “Can a single bubble sink a ship?,” *Am. J. Phys.* **71**, 842–849 (2003).

<sup>7</sup>K’NEX is a brand name of a construction toy system, which uses plastic parts that snap together.

<sup>8</sup>Reference 6, p. 843.

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